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THE BEHAVIOR OF PARTICLES OF RADIATION BELTS DURING MAGNETIC STORMS

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SUMMARY

Radial displacement of particles in radiation belts induced by universal magnetic storms are considered. The source of the disturbance lies in the ring current within the magnetosphere and in the current at the magnetosphere boundary, created by the solar wind. Only the first harmonic (uniform component) of the disturbance field is taken into account from the first source. For the majority of the particles of the fields, this leads to reversible displacements. Particles with reflection points, low-disposed above the ground, in the process of radial transition of shells, may be lowered into the dense layers of the atmosphere and dumped. The concrete examples of the storms of 12 and 20 February 1964 are examined.

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The behavior of energetic trapped particles during storms is determined by the character of the disturbances. Important for the formation of the distribution of long-lived particles are the disturbances leading to irreversible displacements of particles between magnetic shells. The disturbances related to them are those having an azimuthal asymmetry (relative to the undisturbed field) and an asymmetry in time. These can be universal, large-scale disturbances (for example, the variations of a quadruple harmonic dependent upon the longitude considered in[1-3] or the convection in the magnetosphere, engendered by the rotation of the Earth[4-5]) and small-scale disturbances (for example, hydromagnetic waves[6]).

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* O POVEDENIY CHASTITS RADIATSIONNYKH POYASOV VO VREMYA MAGNITNYKH BUR'

Irreversible displacements of particles between magnetic shells, induced by the disturbances, take place at disruption of the third invariant of motion of particles in the magnetic field; under the action of hydromagnetic waves, the second invariant of motion can be disrupted also.

In the present note, we are considering the radial displacements of particles with magnetic shells under the action of a universal disturbance component of the magnetic field during magnetic storms, limiting ourselves only the first harmonic of the disturbance field—by the uniform field perpendicular to the equatorial plane. During the storm the first harmonic undergoes the greatest variation and induces the greatest radial displacement of particles. For the bulk of the particles of the radiation belts, however, these displacements are reversible; after the restoration of the field, the particles, intersecting the equator under small pitch-angles, the reflection points of which lie relatively closely to the ground, may be the only exception. In the process of reversible radial transitions, their reflection points can be lowered still further into the dense layers of the atmosphere, leading to particle dumping. We will consider in which cases this is possible.

In the assumption that the wind velocity is perpendicular to the dipole moment, the dipole field of the Earth distorted by the solar wind on the equator can be described with sufficient precision by three terms

$$B = \frac{B_0}{r^3} + \alpha \frac{B_0}{r_1^3}\left(1 + \beta \frac{r}{r_1} \cos\lambda\right), \tag{1}$$

the first of which represents the field of the undisturbed dipole, the second--the uniform field (the first harmonic of expansion by the spherical function of the outer source field), the third—the part of the disturbance field (the second harmonic of expansion, the quadruple term), asymmetric by the longitude λ. Here $B_0 = 0.31$ gauss is the field on the ground at the equator, r is the distance from the center of the Earth to the fixed point in the equatorial plane, $r_1 = (B_0 2/2\pi P_d)^{1/6}$ is the distance to the midday magnetosphere boundary (both quantities are expressed in Earth radii R_E), $P_d = 2$ mnv is the dynamic pressure of the solar wind. The coefficients α and β are determined by the shape of the magnetosphere surface, dependent in its turn on the parameters of the solar wind, the dynamic pressure P_d and the hydrostatic heat pressure P, directed along the wind. The various approximations give values α and β somewhat differing in magnitude. In model [7], describing the magnetosphere boundary from the midday side of the surface, the closest coinciding with the experimental ones (the temperature of the flux is assumed to be zero, P = 0) are the coefficients

$\alpha = 0.80$, $\beta = 0.55$. In the more simple and rough model of the generalized method of the imaginary dipole of [8], $\alpha = 0.35$, $\beta = 0.90$. In both cases the second harmonic is essentially smaller than the first through $r \sim 0.7\ r_1$. At comparison by the spherical surface of the radius r_1, only the first harmonic with $\alpha = 2$ exists. The second harmonic of the disturbance field is relatively large only in the roughest of the utilized models, that is, at compression of the dipole by the plane to the distance r_1. In this model $\alpha = 1/8$, $\beta = 3/2$.

When computing radial displacements of particles at variation of r_1, we will consider only the first harmonic. In this assumption, the third invariant of motion is preserved independently from the rate of the variation r_1, since the disturbance does not depend upon the longitude. Therefore, the displacement of particles can be found from the condition of preservation of the third invariant, that is, of the magnetic flux Φ through the equatorial cross-section of the magnetic shell $r = L$, which in the given approximation, is a circle. We have

$$\Phi = 2\pi B_0 \int_0^L \left(\frac{1}{r^3} + \frac{\alpha}{r_1^3}\right) r dr = -\frac{2\pi B_0}{L}\left\{1 - \frac{\alpha}{2}\left(\frac{L}{r_1}\right)^3\right\}. \qquad (2)$$

We took advantage of the fact that for the dipole the flux inside the shell L equals the flux with the opposite sign outside the shell L. At $\delta L/L \ll 1$, $\delta r_1/r_1 \ll 1$, we shall obtain from the condition $\delta\Phi = 0$

$$\delta L = \delta r_1 \frac{3/2\,\alpha (L/r_1)^4}{1 + \alpha (L/r_1)^3}. \qquad (3)$$

In the first phase of the storm δr_1 is negative (the boundary approaches the Earth) and the equatorial distance to the shell decreased also ($\delta L < 0$).

As an example, we shall examine the storms of 12 to 14 February and 20 to 21 February 1964 for which a great quantity of data is available in [9].

As is shown in work [9], the storms of 12 to 14 February 1964 took place in the following manner: at the time of the first phase of the storm, the period of type--Pc oscillations is decreased, the magnetic field in the magnetosphere (on the surface of the Earth as well as at high altitudes) is increased, the outer boundary of the belt of electrons with energy $E_e \gtrsim 150$ kev shifts to the side of the smaller L, the anomalous absorption of cosmic radioemission takes place at high latitudes from the daytime side of the Earth. At the time of the development of the main phase of the storm, the period of oscillation of the type-Pc remained small, the magnetic field on the ground is decreased, but at great altitudes, it is increased. The boundary of the radiation belt was displaced to smaller L. Anomalous absorption of radionoise was observed at a series of stations at high latitudes. The general conformity of behavior of the universal component of the magnetic field at the time of these storms is in agreement with the generally accepted picture (see, for example [10]) and with these peculiarities of the storm development which are emphasized in [8, 11].

The displacement of the boundary r_1 during the storm of 12 to 14 February can be estimated by the decrease of the period $T \sim r_1^4$ of short periodic oscillations of the type-Pc. At the time of the first phase, their period decreased from 50 to 15 sec [12]. If these oscillations have a resonant character and are connected with the dimensions of the magnetosphere from the midday side, then $T \sim \int_0^{r_1} dr/V_A$, where V_A is the Alfvén velocity. At constant density of the magnetosphere plasma ρ and $B \sim r^{-3}$ and the period $T \sim r_1^4$. The empirical dependence has the form $T \sim r_1^{4.8}$ [12]. Since for the undisturbed magnetosphere $r_1 = 10$, the decreases of the period from 50 to 15 sec correspond to $\delta r_1 = -2.3$. The radial displacement of particles will be determined by (3). For example, at $L \sim 6$, $L \approx 0.45\alpha/(1 + 0.21\alpha) \approx 0.3$ for the model [7] at $\alpha \approx 0.8$ (for the sphere $\delta L \approx -1$ at $\alpha = 2$). Qualitatively this corresponds to the observed displacement of the conditional boundary of the electron belt with $E_e \sim 150$ kev from $L \sim 6$ to $L \sim 5$ [9, Fig. 3.6]. At comparison, we should take into account the longitudinal asymmetry of the belt which, in the experiment, is found to be somewhat greater than any other of the accepted models of the magnetosphere, and also the betatron acceleration of electrons at displacement to smaller L, which at a fixed threshold response of a counter can increase the apparent effect of the boundary shift.

The growth of the horizontal component of the field on the equator is determined by the second term in (1) at variation of r_1 from ~ 10 to ~ 7.7. It is equal to $\delta B \sim 30\gamma$ or taking into account the diamagnetic effect of the Earth $\delta B \sim 45\gamma$ at $\alpha = 0.80$. This qualitatively agrees with the observed increase of the horizontal component $40 \div 80\gamma$ during the storm 12 to 20 February [9]. Here we should take into account the possible compression of the magnetosphere tail at the time of the first phase of the storm which corresponds to the increase of the coefficient α and, consequently, to the increase of the growth effect of the horizontal component [8].

The shift of particles of the belt on the smaller distance L in the first phase of the storm will be attended by lowering of the reflection points and the dumping into the atmosphere of particles with low-disposed reflection points. The variation of the heights of the reflection points at transition from the distances L on $L' = L + \delta L$ is determined by the first and the second invariants of motion

$$v^2 \sin^2 \theta_0 / B_0 = v^2 / B_m = \text{const}, \quad I \sim vL = \text{const} \tag{4}$$

(The expression for the second invariant is written in the approximation valid for great latitudes and small pitch-angles). Since the intensity of the magnetic field at the reflection point B'_m and the pitch-angle θ'_0 on the equator after the transition is determined by the expressions:

$$(B_m'/B_m)^{1/2} = \sin^2 \theta_0' / \sin^2 \theta_0 = L/L' \tag{5}$$

In the dipole approximation

$$L^3 \sin^2 \theta_0 = (1 + h)^3 \left[4 - \frac{3}{L}(1 + h)\right]^{-1/2} = f(h, L) \tag{6}$$

where h is the height of the reflection point in the Earth's radii Expanding $L'/L = f(h', L')/f(h, L)$ by $h \ll 1$ and $\delta L/L$, we shall obtain *

$$\delta h = h' - h = 2/3 \, (\delta L/L) \tag{7}$$

If we utilize the experimental value of [9] of the boundary drawing of the belt of electrons with energies $E_e \sim 150$ kev $\delta L \approx -1$ at $L \sim 6$, the reflection points will be lowered by $R_e \, \delta h \approx -700$ km (Model(7) $\delta L \approx -0.3$ would give a lower value of ~ 200 km). The flux of escaping electrons may be roughly estimated in the assumption of their isotropic destruction by pitch-angles along the line of force and neglecting the widening of the tube of force of the magnetic field at the distance $R_E \, \delta h$. Under these conditions the flux of escaping electrons is

$$j \approx j_0 R_E \, \delta h / v\tau \tag{8}$$

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* It is interesting to compare this lowering effect of reflection points with the lowering effect at the internal transition of particles with L on L' at the preservation v in (4) (the current therefore is not preserved). At these assumptions $L \gg 1$, $h \ll 1$, we shall obtain $\delta h_v \sim \delta h (3/16 \, L)$, that is at a much smaller lowering of reflection points, practically determining the lowering of the line of equal B_m with the latitude.

where j_0 is the flux of electrons at the equator, v is their velocity; τ is the time during which all electrons located in a tube of 1 cm^2 cross-section and $R_E\,\delta h$ in length escape at the tightening of the belt. Electrons with energies $\sim$150 kev may penetrate to the altitude $\gtrsim$75 km, whereas their flux on the equator is $j_0 \sim 10^6 cm^{-1} sec^{-1}$. If we assume the "pouring out" time equal to 1 hour, then $j(E_e > 150$ kev$) \sim 20$ electrons/cm^2sec. This value is somewhat smaller but still quite close to the estimate of the electron flux of[13], necessary for the increase of ionization in the D-layer at a height of $\sim$70 km during disturbances by one order of magnitude. The anomalous absorption of cosmic radioemission observed during the storm of 12 and 20 February 1964 at the latitude boundary of the belt[9] can be induced precisely by such an agent.

The dependence of δh on L at fixed tightening of the magnetosphere δr_1 will be obtained from (3) and (7)

$$\delta h = \frac{\delta r_1}{r_1} \frac{\alpha(L/r_1)^3}{1+\alpha(L/r_1)^3}. \qquad (9)$$

Such an increase of δh and consequently also of the dumping with latitude down to the boundary of the belt of energetic electrons is in agreement with the experimental data on anomalous absorption of the galactic radioemission[9].

We will examine the main phase of the magnetic storm during which the horizontal component of the field at low latitudes on the ground decreased. The decrease of the horizontal component is ascribed to the diamagnetic action of the ring current of western direction, forming in the magnetosphere at a distance $R \sim 3$-5 radii from the center of the Earth. The formation of the ring current can be connected with the heating of the innermost dense layers of the magnetosphere by hydrodynamic waves, propagating from the boundary of the magnetosphere into the depth at the time of solar wind intensification. In the final count, the magnetosphere as a whole is expanded to dimensions exceeding the preliminary undisturbed volume[11]. However, the development of such a ring current and the lowering of the horizontal component of the magnetic field may originate in conditions of continuing growth of solar wind pressure. In this case, the diurnal boundary of the magnetosphere continues under specific conditions to approach the Earth. The growth of the horizontal component at low latitudes, connected with the intensification of the current of eastern direction on the magnetosphere boundary at its proximity to the Earth, is concealed by the stronger effect of the horizontal component decrease by the field of the ring current disposed nearer to the Earth.

The field of the ring current can be approximately presented as the field of a current of westerly direction on the surface of a sphere of radius R distributed along the surface with a density $j \sim \cos\phi$ (ϕ is the latitude). The field of such a sphere is equivalent to the field of a uniform magnetized sphere with the moment $\delta M = kM$ (M is the magnetic moment of the Earth) giving for $r > R$ the uniform field $2B_0/R^3$ and the dipole field kB_0/r^3 for $r > R$. Taking into account only the uniform part of the perturbation field from the boundary of the magnetosphere, we will have for the equatorial plane

$$B(r) = B_0\left(\frac{1}{r^3} + \frac{\alpha(1+k)}{(r_1')^3} - \frac{2k}{R^3}\right) \qquad r < R, \tag{10}$$

$$B(r) = B_0\left(\frac{1+k}{r^3} + \frac{\alpha(1+k)}{(r_1')^3}\right) \qquad r > R. \tag{11}$$

The distance r_1' to the disturbed midday boundary of the magnetosphere is connected with the undisturbed value r_1 (prior to the intensification of the solar wind and the emergence of the ring current) by the expression

$$r_1' = r_1(1+k)^{1/3}\left(\frac{P_{d_0}}{P_d}\right)^{1/6} = r_1\left(\frac{1+k}{\Pi}\right)^{1/3}, \tag{12}$$

where $\Pi = (P_d'/P_d)^{1/2} = (nv^2/n_0v_0^2)^{1/2}$ characterizes the degree of increase of the solar wind pressure.

With the aid of (12), the first harmonic can be expressed by the undisturbed value of the distance r_1 to the boundary

$$B(r) = B_0\left(\frac{1}{r^3} + \frac{\alpha\Pi}{r_1^3} - \frac{2k}{R^3}\right) \qquad r < R, \tag{13}$$

$$B(r) = B_0\left(\frac{1+k}{r^3} + \frac{\alpha\Pi}{r_1^3}\right) \qquad r > R. \tag{14}$$

At the time of the developed main phase the third term predominates in (13). The typical values of the magnetic moment of the ring current $k = \delta M/M \approx 0.1$, for example, at $R \sim 4$ and $\Delta H = B(1) \approx -100\,\gamma$.

The radial displacement of particles at distortion of the dipole field by the two examined sources will be determined from the condition of preservation of the third invariant. The flow across the equatorial cross-section of the perturbed shell $L' = L + \delta L$ in the region $L' > R$ will be obtained from (11) (as earlier, when deriving (3), the integral from the dipole part of the field along the region $r > L$ we substitute the integral with the reverse sign over the outer part $r > L$ of the dipole field)

$$\Phi' = -\frac{2\pi B_0(1+k)}{L'}\left\{1 - \frac{\alpha}{2}\left(\frac{L'}{r_1'}\right)^3\right\}. \tag{15}$$

Equating Φ' by the undisturbed value Φ at $k = 0$, $L' = L$, $r_1' = r_1$ and exapanding by $\delta L/L$, we shall have

$$\frac{\delta L}{L} = \frac{k - {}^1/_2\alpha(L/r_1)^3\,\delta\Pi}{1 + \alpha(L/r_1)^3(1 + {}^3/_2\,\delta\Pi)}. \qquad (16)$$

At $k = 0$ and $\delta\Pi = 3\delta r_1/r_1 \ll 1$ this expression is passed to (3).

During the development of the main phase, the particles can pass to much deeper levels ($\delta L < 0$) only for a specific correlation between the coefficients, characterizing the rise of solar wind pressure $\delta\Pi$ and the development of the ring current k, determining the requirements that the second term in the numerator of (16) be greater than the first. Since $(\alpha/2)(L/r_1)^3 < 1$, there must knowingly be $k < \delta\Pi$ and, as is evident from (12), the boundary must then be approaching the Earth. Therefore, even at ring current the necessary condition for a reversible transit of particles with low-disposed reflection points in the region $L > R$, is the contraction of the magnetosphere. The ring current only limits and does not arrest at all this effect.

The variation of the horizontal component of the field on the Earth's surface at the equator relative to the undisturbed level $H_0 = B_0(1 + \alpha/r_1^3)$ will be determined by formula (13) at $r = 1$

$$\Delta H = H - H_0 = B_0[(\alpha\delta\Pi / r_1^3) - 2k / R^3]. \qquad (17)$$

(Here the analogy between the parameters $\delta\Pi = \Pi - 1$ and k, defining the contribution by the surface and ring currents is clearly outlined).

In order to determine whether dumping is generally possible by ground measurements during the main phase, we shall require the simultaneous fulfillment of the condition $\delta L < 0$ in (16) and $\Delta H < 0$ in (17). Then we shall obtain

$$1 / L^3 < 1 / L_0^3 = \alpha\delta\Pi / 2kr_1^3 < 1 / R^3. \qquad (18)$$

It is obvious that both inequalities can be satisfied. The quantity L_0 defines the lower limit of the radial values of L (the upper limit being $L \leqslant r'$), from which these particles shift into the depth of the magnetosphere, provided the latter's contraction from r_1 to r_1' takes place simultaneously with the development of the ring current (when its magnetic moment increases from 0 to k). From (16) and (18) we may write

$$L_0^3 = \frac{R^3}{1 - (\Delta H/\Delta H_R)}, \qquad \Delta H_R = -2kB_0/R^3, \qquad (19)$$

where ΔH_R is the decrease of the horizontal component at the equator on account of the ring current. The smaller it is, that is, the lesser the magnetosphere squeezing for the given ΔH, the higher the boundary L_0 of the possible particle dumping.

It is impossible to separate the contribution to the disturbance of the horizontal component of magnetosphere boundary from that of the contribution of the ring current. If, moreover, the variation r_1 is clear (from direct measurements on satellites or by the variation of the period of micropulsations), we may determine from (19), (17) and (12) the parameter r and R of the ring current of which the measurements are otherwise of so difficult an access.

The reasonings brought out concern the simultaneous compression of the magnetosphere boundary and the formula of the ring current. However, the latter, linked with the dissipation of hydromagnetic waves in the magnetosphere usually lags in the development relative to the fast variations of the distance to the daytime boundary of the magnetosphere. In this case, it plays no part, and the radial transits of particles are determined with the respective normalization of the initial values as in the first phase.

The separate outbursts of escaping particles during the main phase of the showers of 12 and 20 February, which may be seen in Fig. 6.9 of the work [9], are apparently due to impulse contraction of the magnetosphere during the times when the ring current cannot vary substantially.

During the main phase of the storms of 12 and 20 February the lowering the horizontal component was small $\Delta H \sim -40\gamma$. The growth of the ring current at the commencement of the main phase took place concomitantly with the tightening of the boundary from $r_1 \sim 10$ to $r_1' \sim 8$. The characteristic of L_0 is difficult to determine from the data of [9]. This is why we adopt $R \sim 4$. From (12) at $k \ll 1$, we have $\delta\Pi = \Pi - 1 \approx 1$. From (17) $k = 6.9 \cdot 10^{-2}$ at $\alpha = 0.85$. This gives $\Delta H_R = -68\gamma$ and $L_0 \sim 4.5$. Therefore, the feeble lowering of the horizontal component during the main phase could not hinder the dumping of the particles, induced by the contraction of the daytime boundary of the magnetosphere.

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